GPS MEASUREMENTS OF CRUSTAL DEFORMATION ASSOCIATED WITH THE 22 APRIL 1991, VALLE DE LA ESTRELLA, COSTA RICA EARTHQUAKE

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Abstract. We present analysis results for Global Positioning System (GPS) measurements made at sites in Costa Rica during two campaigns in February and July 1991. GPS solutions for 5 sites (Limon, Liberia, Bratsi, ETCG, and Vueltas) reveal significant horizontal and vertical displacements relative to their February positions. Horizontal displacements relative to Liberia, measured 244.7 ± 0.8, 89.2 ± 0.9, 12.4 ± 1.3, and 1.9 ± 0.9 cm at Limon, Bratsi, Vueltas, and ETCG respectively. Vertical displacements relative to Liberia measured 16.3 ± 2.1, 15.3 ± 3.0, -10.5 ± 4.4, and -0.6 ± 2.1 cm at Limon, Bratsi, Vueltas, and ETCG respectively. We find differences in the GPS derived vertical and horizontal displacements compared to other types of geodetic measurements of uplift in the coastal region and their associated models. To address these differences we compute a dislocation model which fits the GPS measured displacements. A simple uniform planar slip model can not reconcile the differences between the coastal uplift data or the seismic moment, suggesting considerable complexity of the earthquake source.

Introduction

The April 22, 1991, Valle de la Estrella, Costa Rica earthquake was a large earthquake (m_b=6.3, M_S=7.6, M_W=7.7 from the NEIC) which caused large amounts of uplift from Limon to the Panama border along the Caribbean coast [Plafker and Ward, 1992].

In January - February of 1991, Global Positioning System (GPS) measurements were taken at several sites in Costa Rica as part of the CASA and CORBAS campaigns [Freymueller and Kellogg, 1991; L. Aguilar, unpublished

data]. The existence of these measurements within several months of the earthquake, prompted us to conduct a GPS remeasurement campaign of several of these sites from July 1-11, 1991. In this paper we present displacement results for those February 1991 sites which were remeasured in July 1991, and compare these results to models of the earthquake source. We find significant differences between our GPS measured displacements and models derived for vertical uplift data [Plafker and Ward, 1992] or seismologically constrained models of the source [Goes et al., 1992]. We derive our own slip dislocation model which fits our GPS measurements and investigate differences between these data sets and their associated models in light of unmodeled slip heterogeneity on the fault and post-seismic displacements.

22 April 1991 Earthquake and Tectonics

The 22 April 1991 earthquake (Figure 1) occurred along the westernmost extent of the North Panama Deformed Belt (NPDB), a diffuse zone of crustal folding and thrust faulting to the north of Panama, extending from Colombia to Costa Rica [Adamek et al., 1988; Silver et al., 1990]. The NPDB is defined by seismicity, thrust focal mechanisms, offshore geophysical data, and the continuation of thrust faulting on land in Costa Rica [Case and Holcombe, 1980; Adamek et al., 1988; Silver et al., 1990].

The exact termination of the NPDB, however, remains uncertain, though it has been suggested that it becomes a diffuse zone of left-lateral strike-slip faults which connect the NPDB just NW of Limon to the Middle America trench to the southwest [Jacob and Pacheco, 1991]. The Valle de la Estrella earthquake supports this model with the abrupt termination of coastal uplift immediately to the NW of Limon [Plafker and Ward; 1992] and the occurrence of left-lateral strike-slip earthquake focal mechanisms to the west of Limon [Dziewonski et al., 1992; Goes et al., 1992]. This change in geometry is supported by the SW-NE alignment of aftershocks at the NW end of the rupture zone [Schwartz and Protti, 1991].

GPS Analysis Approach and Results

The GPS data were analyzed to obtain site coordinates using the GIPSY (GPS Inferred Positioning SYstem) software developed at the Jet Propulsion Laboratory [Blewitt, 1989; Lichten, 1990]. The July 1991 (CORI) campaign reoccupied 5 of the Costa Rica sites measured in February 1991 (CASA, CORBAS; hereafter referred to as CASA). Trimble 4000 SST and Trimble 4000 SDT receivers were used at all the Costa Rican sites, in addition to data from a global network of Rogue receivers, for both the CASA and CORI campaigns.

In our analysis estimated parameters included satellite positions and velocities, station positions, satellite and station clocks, zenith tropospheric path delays, and carrier phase ambiguities. GPS data analysis for both the CASA and CORI solutions used in this study followed the GIG'91 analysis [Blewitt et al., 1992], and was independent of CASA GPS solutions presented elsewhere [Freymueller and Kellogg, 1991; Dixon et al., 1992].

The GPS derived baseline components for all stations relative to Liberia are given in Table 1, along with their 1 σ standard deviations. Site displacements are chosen with respect to Liberia since it is the site located farthest from the source region of the earthquake.

We assume that there is insignificant strain accumulation between Liberia and the other sites during the 5 months separating measurements. There is reason to believe that a velocity deficit of ~2 cm/yr occurs at Liberia based on GPS measurements between Cocos Island and Liberia (T. Dixon, pers. communication). This would suggest that over the 5 months between GPS observations there may have been close to 1 cm of NE motion of Liberia with respect to sites less affected by strain accumulation at the Middle America trench, such as Limon and Bratsi, that is not accounted for in our 'co-seismic' displacements. Less relative strain accumulation contamination would be expected at ETCG and Vueltas. For the purposes of this study a systematic bias introduced by assuming fixed Liberia of order 1 cm in the horizontal displacements is not considered significant. Additional sources of contamination such as large earthquakes near Liberia did not occur between GPS occupations.

Since the formal error estimates usually underestimate the variances computed as the baseline repeatability [i.e.

Larsen and Reilinger; 1992] we use a more realistic approach to estimate the displacement errors. We scale the covariance values by a factor of 2, determined by the mean ratio of repeatability in baseline length and the formal error between the first and second halves of each experiment for all common baselines [Blewitt et al., 1992]. Site displacements relative to Liberia are given in Table 2, along with their 1 σ standard deviations in magnitude and direction.

Discussion and Conclusions

The displacements we determined for three sites, BRAT, LIMO, and VUEL, with respect to LBER from GPS measurements within 3 months of the 22 April 1991 Valle de la Estrella, Costa Rica earthquake differ significantly from vertical coastal displacements and slip dislocation models for this earthquake determined by Plafker and Ward [1992]. While only the GPS measured displacements for Limon are directly comparable to any of the Plafker and Ward uplift data, any slip dislocation model produces a large area of predicted deformation which can be compared to other geodetic data not lying on the coast.

Foremost of the differences between our GPS results and the field observations of Plafker and Ward is the small amount of uplift observed at Limon, the only GPS site lying on the coast in the same area as field measurements were made. The vertical displacement found for Limon of 16 $\pm$ 2 cm is significantly less than the 60-84 $\pm$ 20 cm measured in the immediate vicinity by Plafker and Ward. However, our results are similar to the leveling measurement of 23 $\pm$ 12 cm uplift found for the Limon GPS site by De Obaldia et al. [1991], which were made within three weeks prior to the CORI GPS measurements. It should be noted that the GPS and leveling errors are considered to be 1 σ deviations, while the Plafker and Ward measurements are assigned errors based on whether they represented 'good', 'fair', or 'poor' quality.

The GPS derived horizontal displacement of 244 cm is nearly twice as large as co-seismic dislocation models computed by Plafker and Ward [1992] predict [S. Ward pers. comm.]. In a refinement of that model Goes et al. [1992] used a focal geometry derived from seismic wave

analysis and found good agreement with the GPS measured displacement azimuths of Limon and Bratsi, though the magnitude of the GPS displacements remained significantly larger at both Bratsi and Limon than predicted by the Goes et al. [1992] model.

To understand the nature of these discrepancies, we derive a co-seismic deformation model which better fits the GPS measurements and is constrained by their greater spatial distribution. We use an elastic half-space dislocation model [e.g. Mansinha and Smylie, 1971] to calculate co-seismic displacements for the Costa Rica earthquake, using the focal geometry of the Harvard CMT solution (strike 102°, dip 24°, slip 57°; Dziewonski et al., 1992), with the slip magnitude and fault dimensions scaled to match our GPS results for Limon and Bratsi (Figure 2). The fault consists of a rectangular fault 58 km along strike by 49 km wide. The fault dimensions were determined to match the vertical and horizontal displacements at Bratsi and Vueltas. The leading edge of the fault plane contains 3 × 3 km 'holes' spaced 3 km apart where no slip occurred, and is located 2 km beneath the surface. We impose this irregularity to demonstrate that a simple deviation from the purely rectangular, uniform slip model, can produce pronounced undulations in the vertical deformation in the region of maximum uplift while not producing such large effects in the horizontal displacements in this focal geometry.

The slip magnitude needed to match the horizontal displacements at Limon, and Bratsi was found to be about 5.8 m. This gives an earthquake source with a factor of 2 greater slip than most other studies derive [Dziewonski et al., 1992; Goes et al., 1992; Plafker and Ward, 1992] and a similar increase in the scalar moment, M_0. The magnitude and direction of the GPS measured horizontal displacements at Limon and Bratsi agree with the co-seismic deformation model shown in Figure 2. To reconcile the differences in the seismological magnitude and the magnitude implied by a uniform slip dislocation model which best fits the GPS measured displacements we need to invoke slip heterogeneity, post-seismic deformation, or after-slip.

The inconsistency of the Limon vertical displacement derived from GPS or leveling with field measurements by

Plafker and Ward [1992] may be reconcilable by incorporating complexity in the slip distribution near the leading edge of the fault (Figure 2); no liquefaction or damage to the the Limon airport runway surrounding the GPS monument was observed which would account for the smaller than anticipated GPS vertical measurement at Limon. Plafker and Ward [1992] did find some variations from site to site near Limon, though these variations may be attributable to differences in data quality and coastline shape. Concentration of slip and seismic moment near the leading edge of the fault under Limon was found by Goes et al. [1992]. De Obaldia et al. [1991] interpreted the differences they found between the large vertical motions around the Limon peninsula and the smaller uplift to the south (including the Limon GPS site) as evidence that the peninsula moved as a separate block. Models of post-seismic visco-elastic relaxation following a thrust earthquake suggest that for an earthquake of this size less than 5 cm of subsidence might be anticipated after 3 months [Thatcher and Rundle, 1979; Rundle, 1982]; to produce subsidence of 50 cm would require a much lower viscosity in the upper mantle. The last possibility, after-slip, would not seem likely since it would produce the same direction of displacements as the main earthquake; it would have to produce on the order of 100 cm additional horizontal displacement at Limon and would add to the amount of vertical displacement observed by Plafker and Ward [1992].

This suggests that refinements to existing slip dislocation models are required to fit the GPS derived 3-dimensional displacements and meet the seismic magnitude of the earthquake. For the Limon GPS site two different geodetic methods yielded similar vertical displacements (GPS 16 ± 2 cm this study, ground leveling 23 ± 12 cm De Obaldia et al., 1991), suggesting that either the values near the Limon GPS site obtained by Plafker and Ward [1992] (60-84 ± 20 cm) for driftwood are inaccurate, or there was 40-60 cm of post-seismic subsidence, a value not supported by analytic solutions for viscoelastic relaxation [Thatcher and Rundle, 1979; Rundle, 1982]. This study illustrates the importance of conducting post-seismic surveys to quantify the effects of local earthquake deformation on more regional observations of plate motions and plate deformation. While the timing of pre-seismic GPS measurements was somewhat fortuitous, the large signal and

broad spatial distribution of significant measured displacements shows that GPS is a valuable tool for constraining co-seismic deformation and earthquake source processes.

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Fig. 1. *Main map:* Regional tectonic map of Central America including the Harvard centroid-moment tensor focal mechanism and epicenter (star) of the April 22, 1991 earthquake. Black quadrants of the lower focal hemisphere indicate compressional first motions. *Inset:* Map of Costa Rica GPS sites used in this study.

Fig. 2. Comparison between a uniform-slip elastic half-space co-seismic deformation model and the GPS measured displacements. See text for model parameters. *Top:* contours of vertical displacement; contour intervals are 30 cm with solid lines for positive displacements (uplift) and the dotted contour for subsidence. The zero displacement contour is the dashed line. *Bottom:* vector horizontal displacements for the model and the GPS measurements (bold).

Table 1. Station displacements and their 1 σ errors relative to Liberia.

Baseline	→	Disp. (cm)	σ (cm)
LIMO	N	147.96	0.33
LIMO	E	194.90	0.95
LIMO	V	16.28	2.09
BRAT	N	62.78	0.44
BRAT	E	63.40	1.26
BRAT	V	15.30	3.00
VUEL	N	7.85	0.88
VUEL	E	9.63	1.58
VUEL	V	-10.51	4.44
ETCG	N	0.51	0.30
ETCG	E	1.80	0.91
ETCG	V	-0.61	2.08

Table 2. Horizontal displacement vectors with respect to Liberia and their 1 σ errors in magnitude and azimuth.

Site	Displacement (cm)		Direction (°E of N)	
	Mag.	σ	Azim.	σ
LIMO	244.7	0.8	52.8	0.2
BRAT	89.2	0.9	45.3	0.6
VUEL	12.4	1.3	50.8	5.6
ETCG	1.9	0.9	74.2	11.6

Fig1

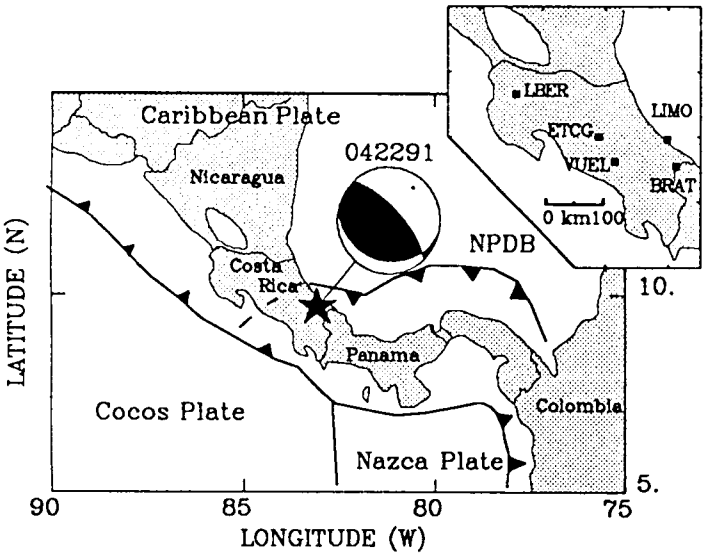
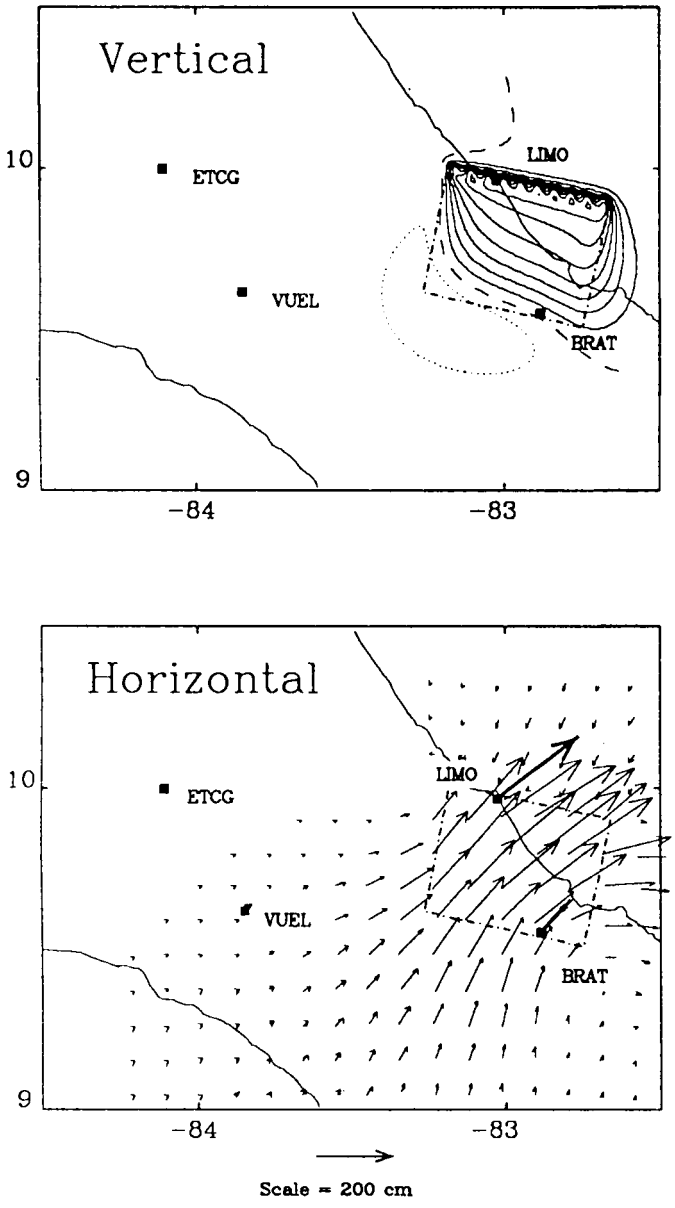

LBER
LIMO
ETCG
VUEL
BRAT
0 km100
Caribbean Plate
042291
Nicaragua
NPDB
Costa Rica
Panama
Colombia
Cocos Plate
Nazca Plate
10.
5.
90
85
80
75
LONGITUDE (W)
LATITUDE (N)

Fig 2


Vertical
10
9
ETCG
VUEL
LIMO
BRAT
-84
-83
Horizontal
10
9
ETCG
VUEL
LIMO
BRAT
-84
-83
Scale = 200 cm